Oak Ridge National Laboratory

Emissions Control for Lean Gasoline Engines

Vitaly Y. Prikhodko (PI)
Email: prikhodkovy@ornl.gov
Phone: 865-341-1459

Oak Ridge National Laboratory
National Transportation Research Center

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- Contributions from the ORNL Team:
  - Todd Toops, Josh Pihl, Jim Parks
- Collaboration with University of South Carolina:
  - Calvin Thomas, Dr. Jochen Lauterbach
- Collaboration with partners at GM:
  - Wei Li, Lei Wang, Pat Szymkowicz, Paul Najt, Arun Solomon
- Collaboration with partners at Umicore:
  - Tom Pauly, Ken Price, David Moser, Sanket Nipunage

Project Overview

Timeline

- Year 1 of 3-year program

  Project start date: FY2019

  Project end date: FY2021
- Builds on previous R&D in FY16-FY18

Budget

- FY19: $500k (Task 3*)

*Task 3: Dilute Lean Gasoline Emissions Control

Part of large ORNL project "Controlling Emissions from High Efficiency Combustion Systems" (2018 VTO AOP Lab Call)

Barriers Addressed

U.S. DRIVE Advanced Combustion & Emission Control 2018 Roadmap Barriers & Targets:

- Lack of cost-effective aftertreatment for lean-burn systems
- Compliance with U.S. EPA Tier 3 Bin 30 emission standard
- Efficiency, durability, sulfur tolerance of aftertreatment systems

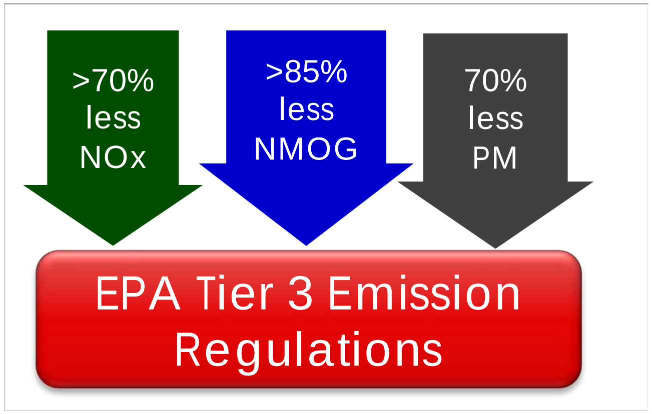
Collaborators & Partners

- General Motors
- Umicore
- University of South Carolina
- Cross-Cut Lean Exhaust Emissions Reduction Simulations (CLEERS)

Objectives and Relevance

Enabling lean-gasoline vehicles to meet emissions regulations will achieve significant reduction in petroleum use

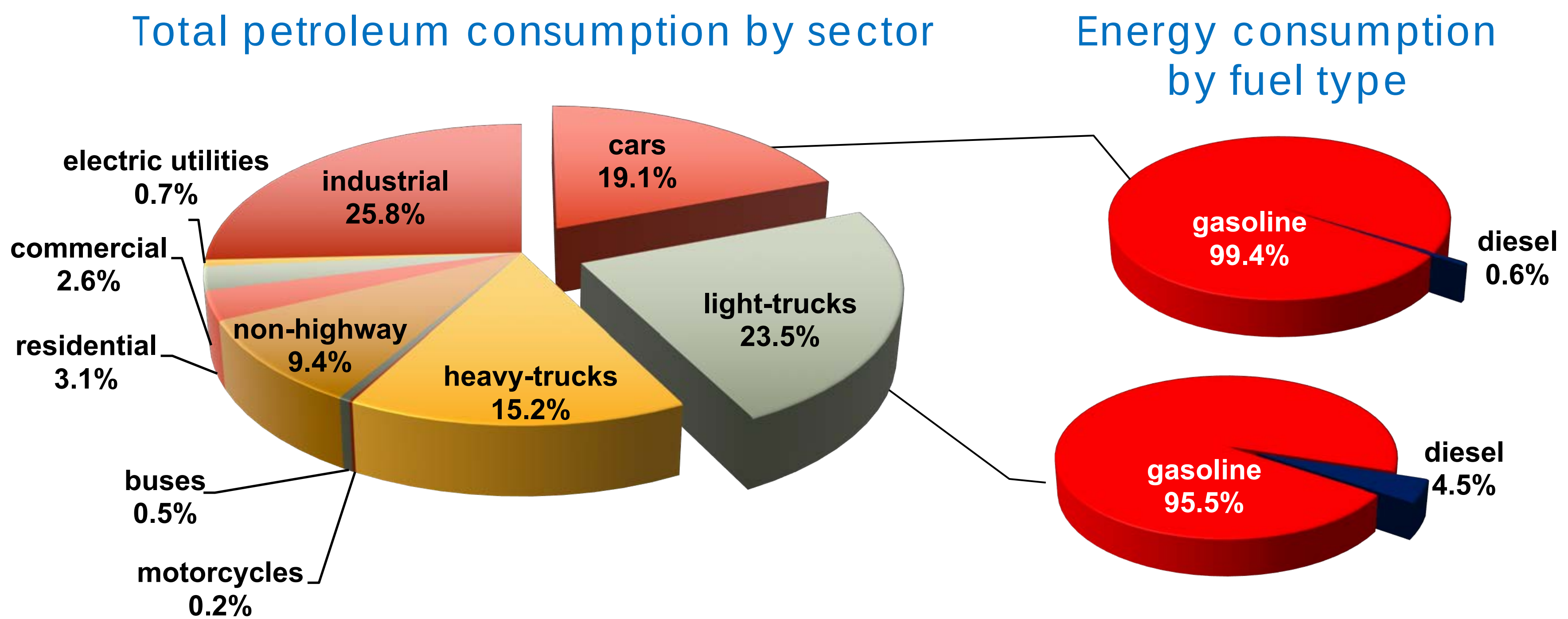
- Objective:
  - Demonstrate technical path to emission compliance that would allow the implementation of lean gasoline vehicles in the U.S. market.
    - Lean vehicles offer 5–15% increased efficiency over stoichiometric-operated gasoline vehicles
    - Compliance required: U.S. EPA Tier 3
  - Investigate strategies for cost-effective compliance
    - minimize precious metal content while maximizing fuel economy



54.5 mpg CAFE by 2025

- Relevance:
  - U.S. passenger car fleet is dominated by gasoline-fueled vehicles.
  - Enabling introduction of more efficient lean gasoline engines can provide significant reductions in overall petroleum use
    - thereby lowering dependence on foreign oil and reducing greenhouse gases

Relevance: small improvements in gasoline fuel economy significantly decreases fuel consumption



- US car and light-truck fleet dominated by gasoline engines
- 10% fuel economy benefit has significant impact
  - Potential to save 13 billion gallons gasoline annually
- HOWEVER…emissions compliance needed!!!

Lean gasoline vehicles can decrease US gasoline consumption by ***~13 billion gal/year***

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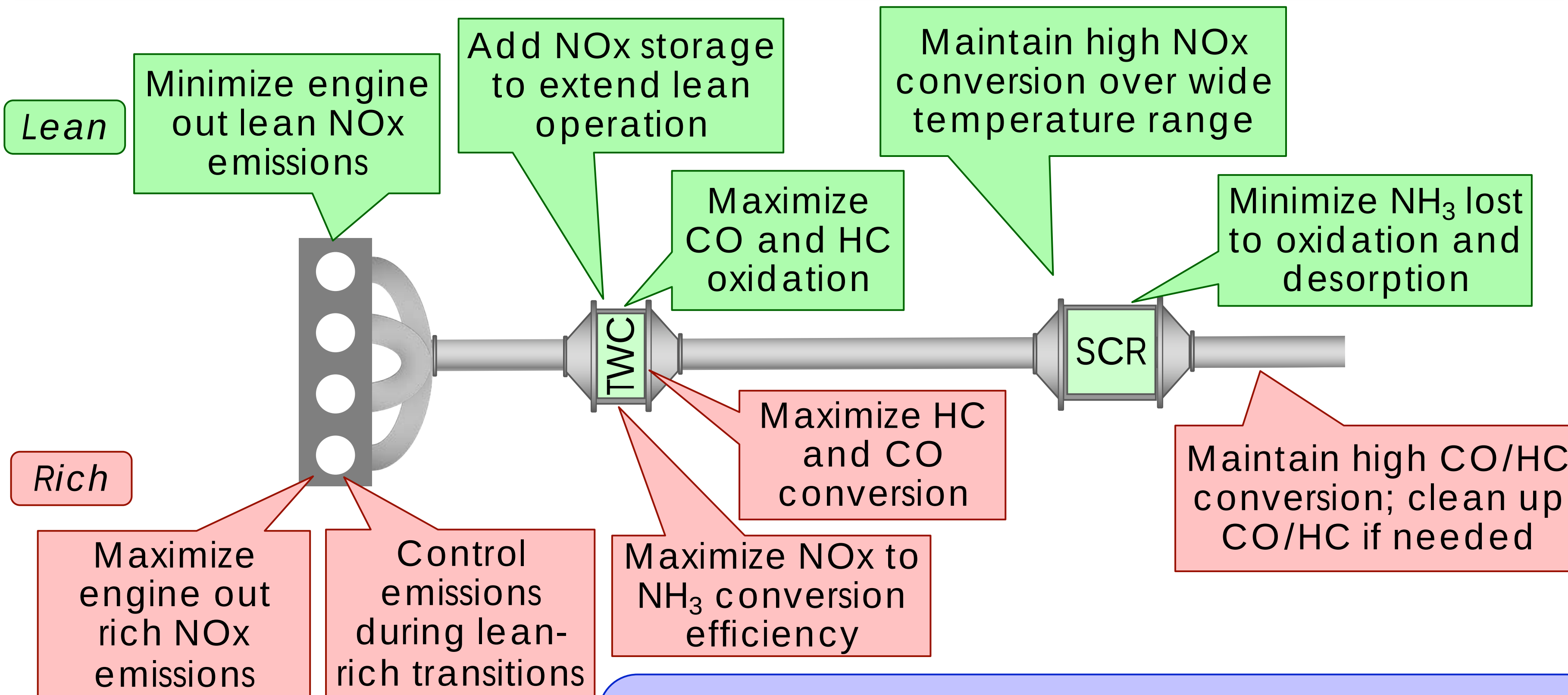
Ref: Transportation Energy Data Book, Ed. 36.1, 2018 (2015 data)

Approach focuses on catalyst and system optimization of passive SCR (and LNT+SCR)

Key Principle: system fuel efficiency gain depends on optimizing NH_3 production during rich operation and NOx reduction during lean operation



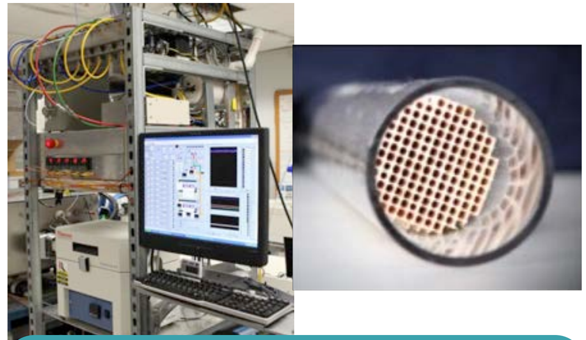
Other Core Principles:

- Expand operating temperature range
- Evaluate durability to hydrothermal aging and sulfur
- Understand precious metal utilization to minimize cost

Refs: SAE2010-01-0366, SAE2011-01-0306

Iterative flow reactor + engine study approach

BMW 120i lean gasoline engine platform with NI open controller



Automated flow reactor with feedback control and tandem catalysts

Aging rig, automated flow reactors, detailed characterization

Define exhaust conditions

Identify formulation impacts on TWC performance

Age, poison, characterize selected TWCs

Measure TWC performance vs. λ

Evaluate SCR formulation effects

Age, characterize selected SCR(s)

Quantify TWC+SCR emissions & fuel efficiency

Investigate alternate catalyst configurations, operating strategies

Optimize combustion parameters and evaluate full system performance

umicore Automotive Catalysts

Prototype Catalysts & Insights

GM

Technical Guidance

Collaborations with modeling community and CLEERS

Collaborations and Partners

Primary Project Partners

- GM: guidance and advice on lean gasoline systems via monthly teleconferences
- Umicore: guidance (via monthly teleconferences) and catalysts for studies (both commercial and prototype formulations)
- University of South Carolina (Jochen Lauterbach): Catalyst aging studies with student Calvin Thomas (now post-doc at ORNL)

Additional Collaborators/Partners on Project/Engine Platform (Since Project Inception)

- CDTi: catalysts for studies
- CLEERS: Share results/data and identify research needs
- LANL: Engine platform used for NH_3 sensor study (Mukundan, Brosha, Kreller)
- MECA: GPF studies via NTRC User-Facility contract
- University of Minnesota: Collaboration on DOE funded project at U of Minn. related to lean GDI PM (PI: Will Northrop)
- CTS (formerly FST-Filter Sensing Technologies): FOA project on RF sensors for GPF, SCR, TWC on-board diagnostics
- Tennessee Tech University: Project data being used for lean gasoline emission control system modeling
- DOE VTO Fuel Technology Program: Engine platform used for biofuel-based HC-SCR studies and TWC employed in Co-Optima research
- Hyundai: Engine platform used for Proprietary User Agreement Project
- MAHLE: New ultra lean gasoline engine research platform

R&D Expanded Coverage via Collaborations:

- Lean GDI PM Control
- Sensors
- Modeling
- Fuels

Milestones

Quarterly Milestones

Complete

- FY2019, Q3: Complete evaluation of 5-function emissions control system with cleanup catalyst

On Track

- FY2020, Q4: Complete measurement of fuel economy benefit and emissions using transient drive cycle on the newly installed MAHLE Turbulent Jet Ignition engine

On Track

- FY2021, Q4: Tier 3 Bin 30 level emissions with an advanced engine platform with less than 4 g Pt-equivalent per liter engine displacement

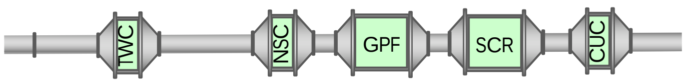
GO/NO-GO Decision

On Track

- FY2019, Q4: Install MAHLE Turbulent Jet Ignition engine at ORNL with full controls which will expand lean operation map for higher fuel efficiency and lower engine out emissions

Summary of Technical Accomplishments

- Demonstrated 8.3% fuel economy improvement with 5-function catalyst system compared to 5.9% with two-catalyst system while meeting Tier 3 NOx+NMOG (0.03 g/mi)



- Procured Mahle Turbulent Jet Ignition engine for lean gasoline emissions control research

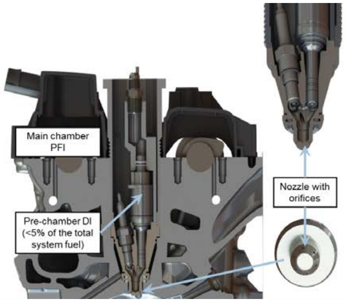
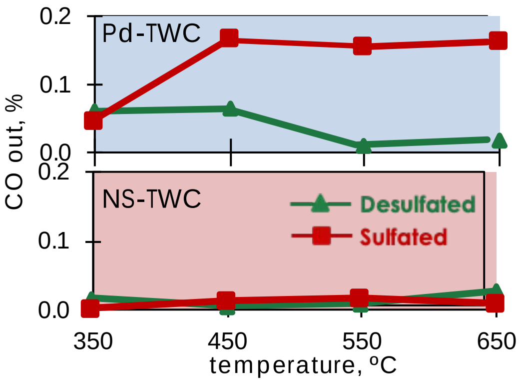


Image from MAHLE

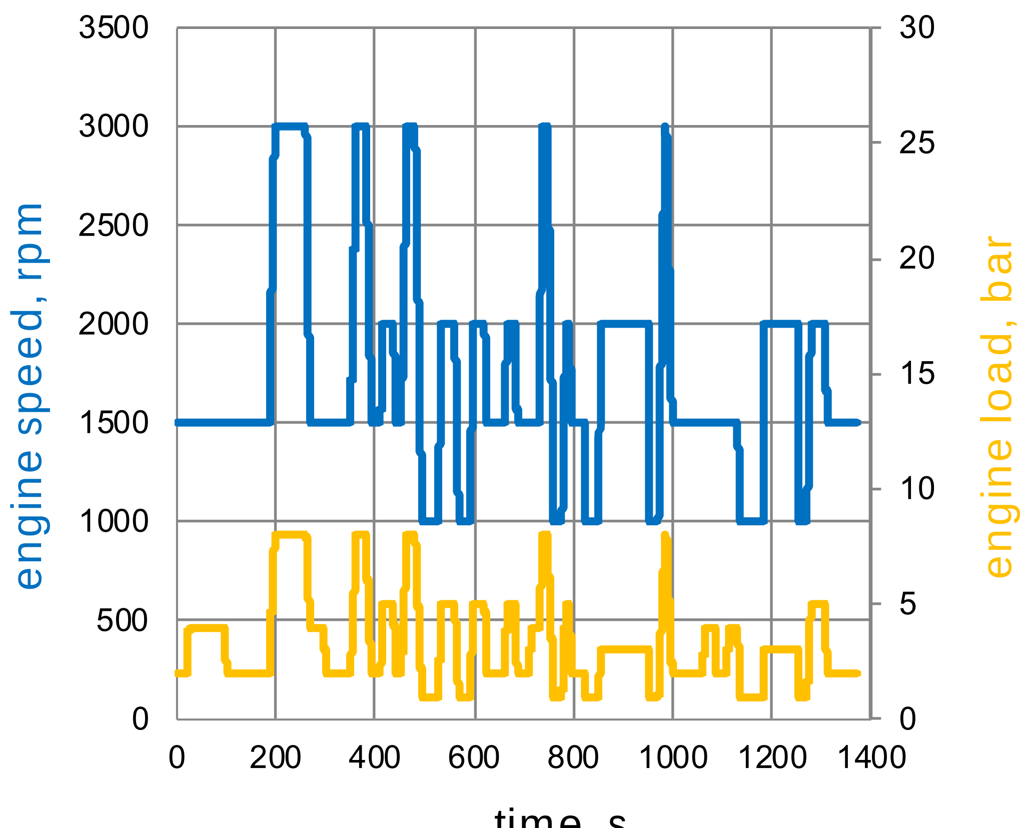
- Competed analysis of sulfur effects on isolated reactions on two TWC formulations (backup slides)
  - Production of NH_3 from H_2 unaffected but decreases from CO and C_3H_8
  - Sulfur impacts on water gas shift and steam reforming reactions varies with formulation

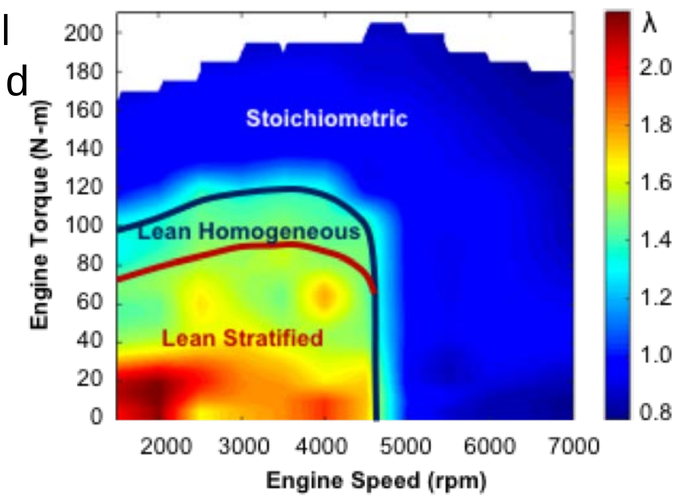


To simulate drive cycle, GM provided 6-mode pseudo-transient cycle utilized for passive SCR evaluation

Operating pseudo-transient cycle closely captures fuel consumption benefit relative to stoichiometric observed on vehicle in study*

- 9.6% with pseudo-transient drive cycle
- 10% with FTP vehicle study





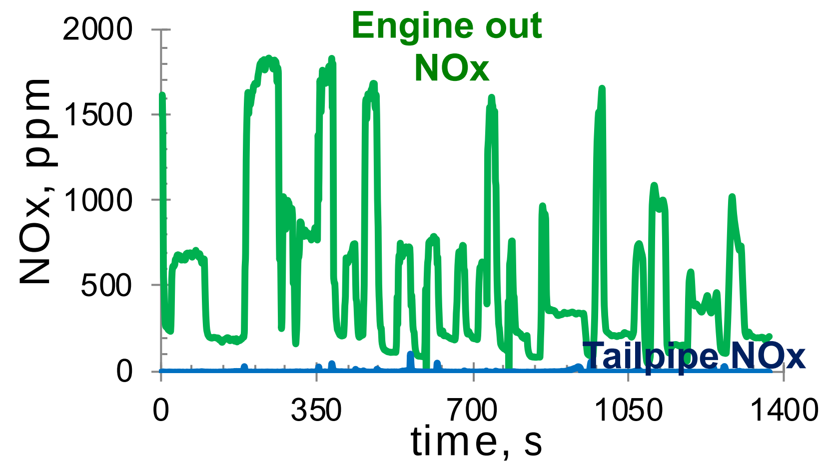
Speed [rpm]	Load [bar]	Default Mode
1000	1.0	LS
1500	2.0	LS
1500	4.0	LS
2000	3.0	LS
2000	5.0	LH
3000	8.0	Stoich

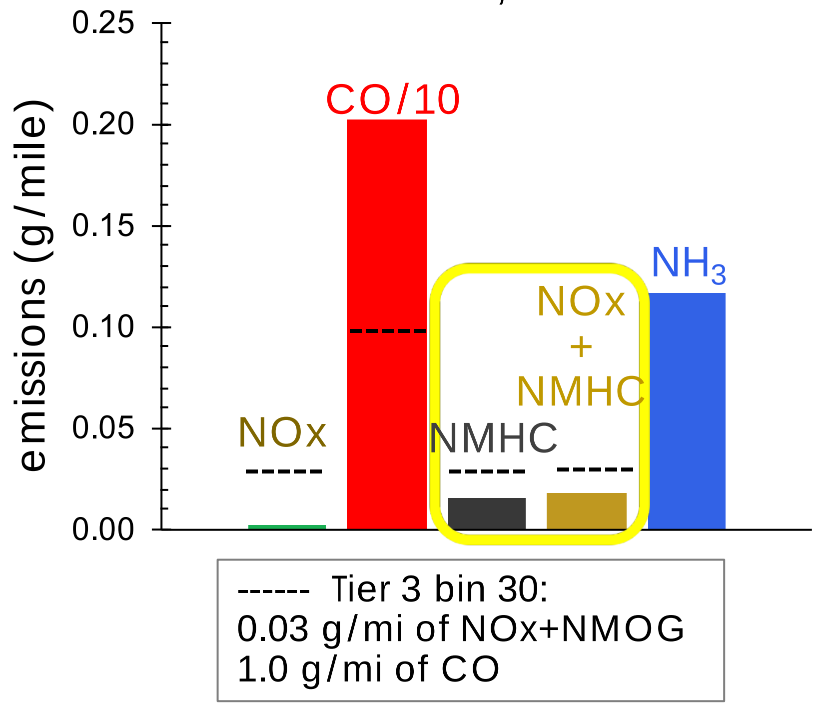
LS=lean stratified, LH=lean homogeneous

** - SAE2010-01-2267, SAE2011-01-1218*

Prior results: U.S. Tier 3 NOx+NMOG emission levels demonstrated with 5.9% gain in fuel economy

- NOx is essentially eliminated
- CO slip is high (2x the limit)
  - clean-up catalyst and/or secondary air injection
- THC slip presented last year was low but close to NOx+NMOG limit
  - Further analysis showed that methane is ~50% of THC slip
- NH_3 slip is high, indicating improved fuel efficiency possible
  - Improved control strategy, additional catalyst technologies



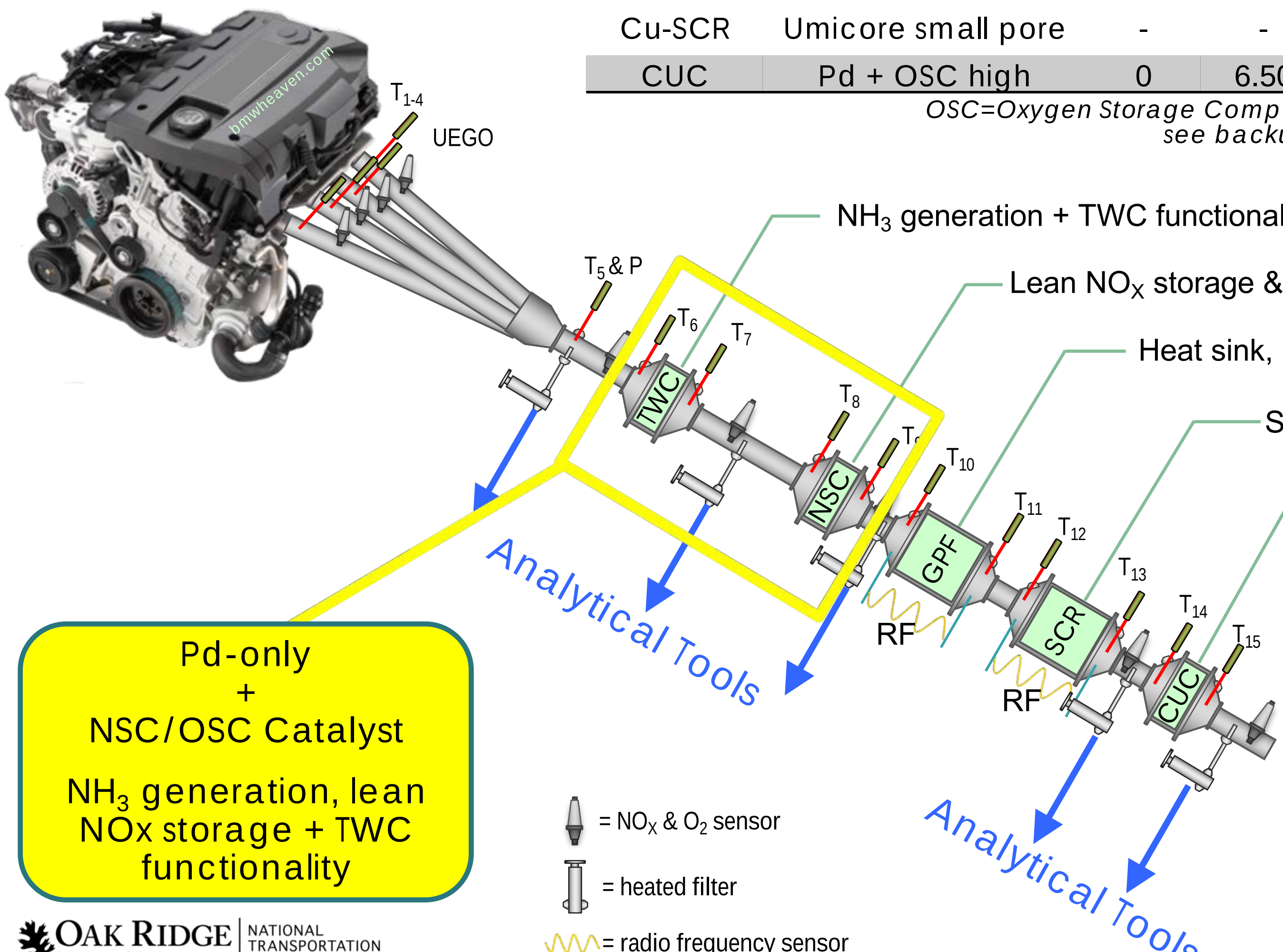


Note: NMHC ~ NMOG for gasoline fuel

Passive SCR system architecture for maximum fuel savings while meeting Tier 3 NOx + HC and CO

sample ID	Description	Pt (g/l)	Pd (g/l)	Rh (g/l)	OSC	NSC	Vol (l)
Pd-TWC	Front half of TWC	0	7.3	0	N	N	0.62
NS-TWC	Pt + Pd + Rh	2.47	4.17	0.05	Y	Y	0.82
GPF	Uncatalyzed GPF	-	-	-	-	-	2.47
Cu-SCR	Umicore small pore	-	-	-	-	-	2.47
CUC	Pd + OSC high	0	6.50	0	H	N	1.00

OSC=Oxygen Storage Component; NSC=NOx storage component
see backup slides for catalyst aging procedure



Pd-only
+
NSC/OSC Catalyst

NH_3 generation, lean NOx storage + TWC functionality

Catalysts aged to full useful life (FUL)

Fuel contained 8 ppm of sulfur

8.3 g/liter-engine total PGM

Some catalyst functions can be combined into one brick

Passive SCR system architecture for maximum fuel savings while meeting Tier 3 NOx + HC and CO

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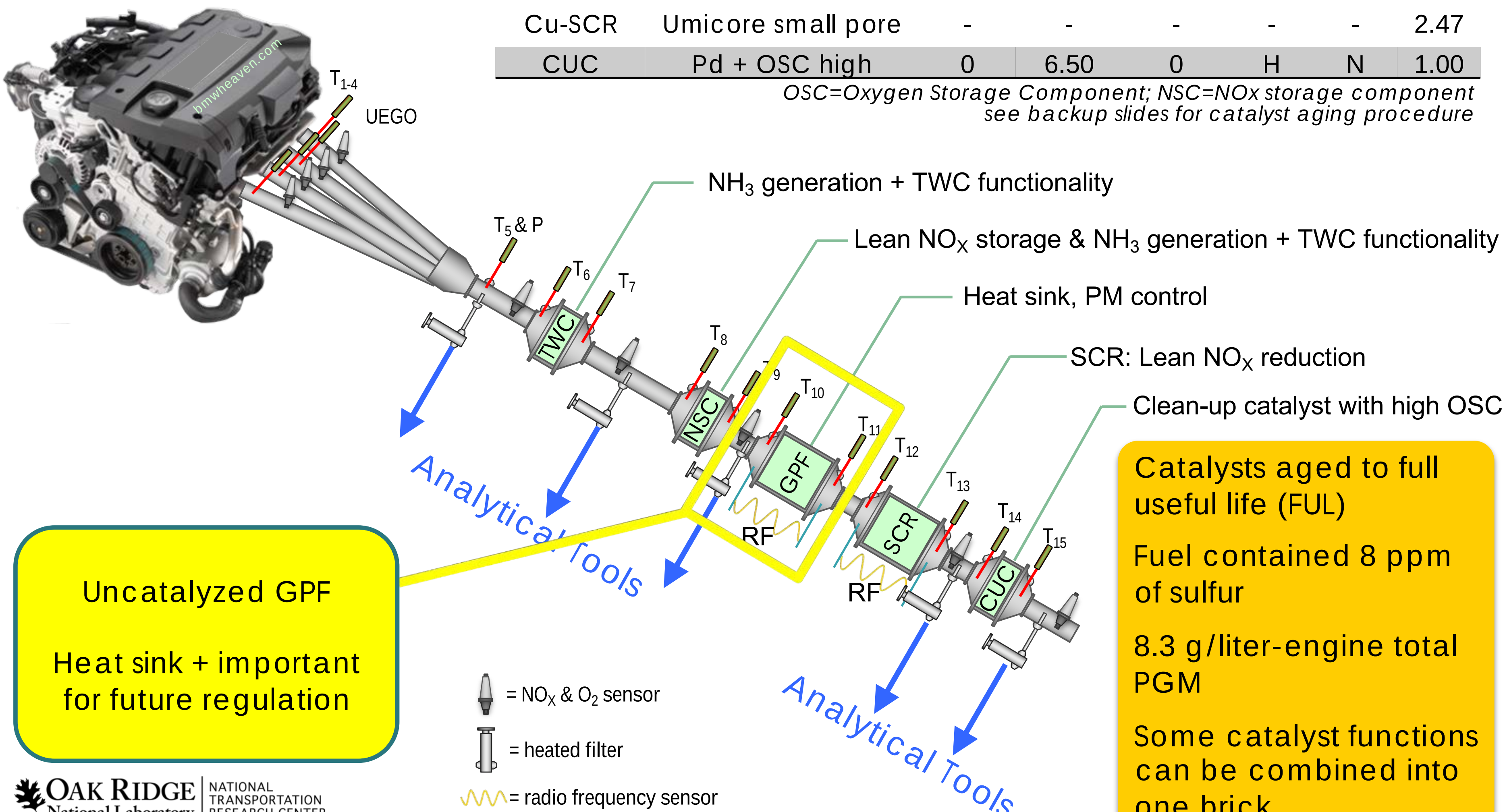

Uncatalyzed GPF

Heat sink + important for future regulation

Catalysts aged to full useful life (FUL)

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Passive SCR system architecture for maximum fuel savings while meeting Tier 3 NOx + HC and CO

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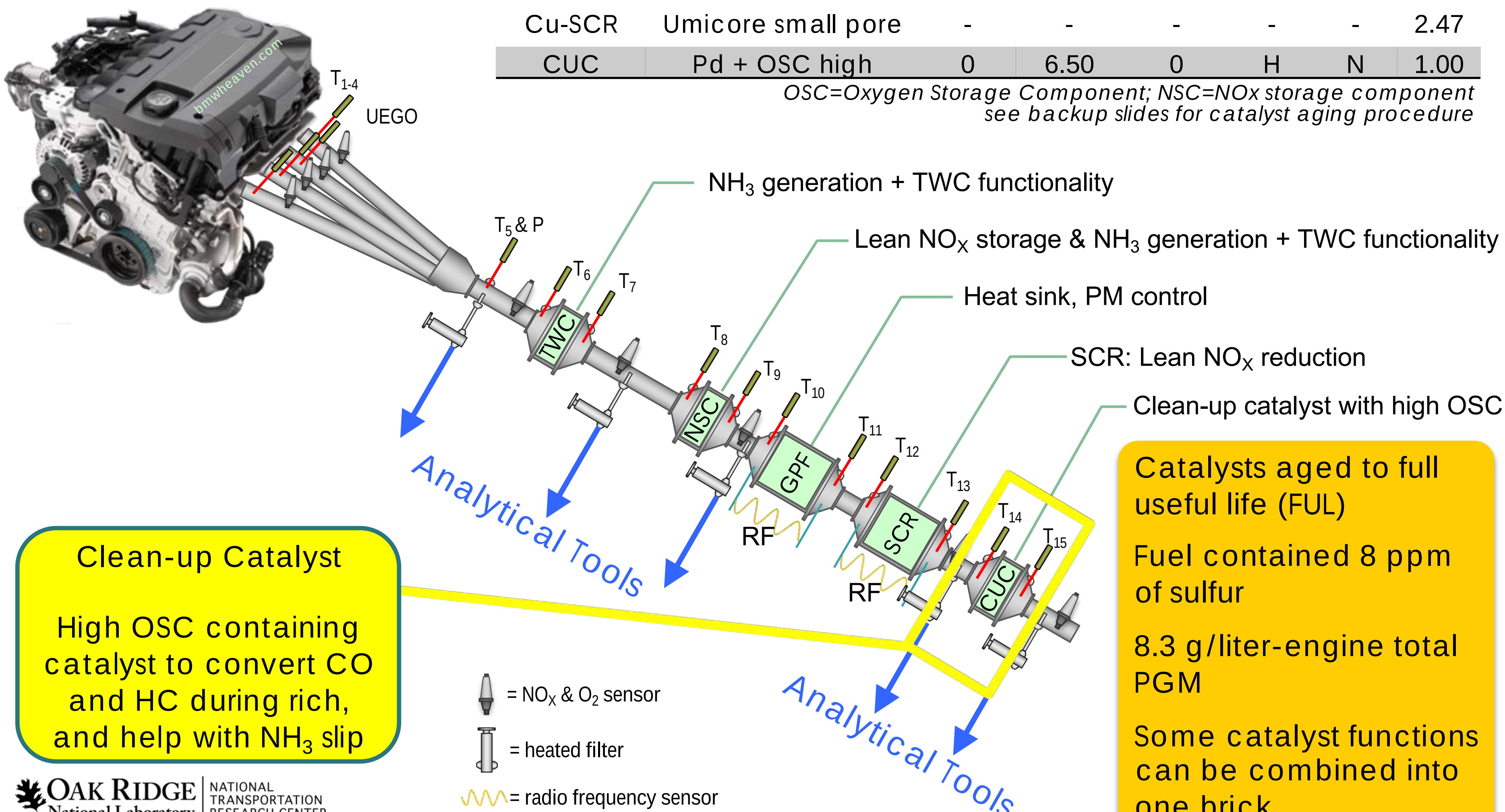


Clean-up Catalyst

High OSC containing catalyst to convert CO and HC during rich, and help with NH_3 slip

Catalysts aged to full useful life (FUL)

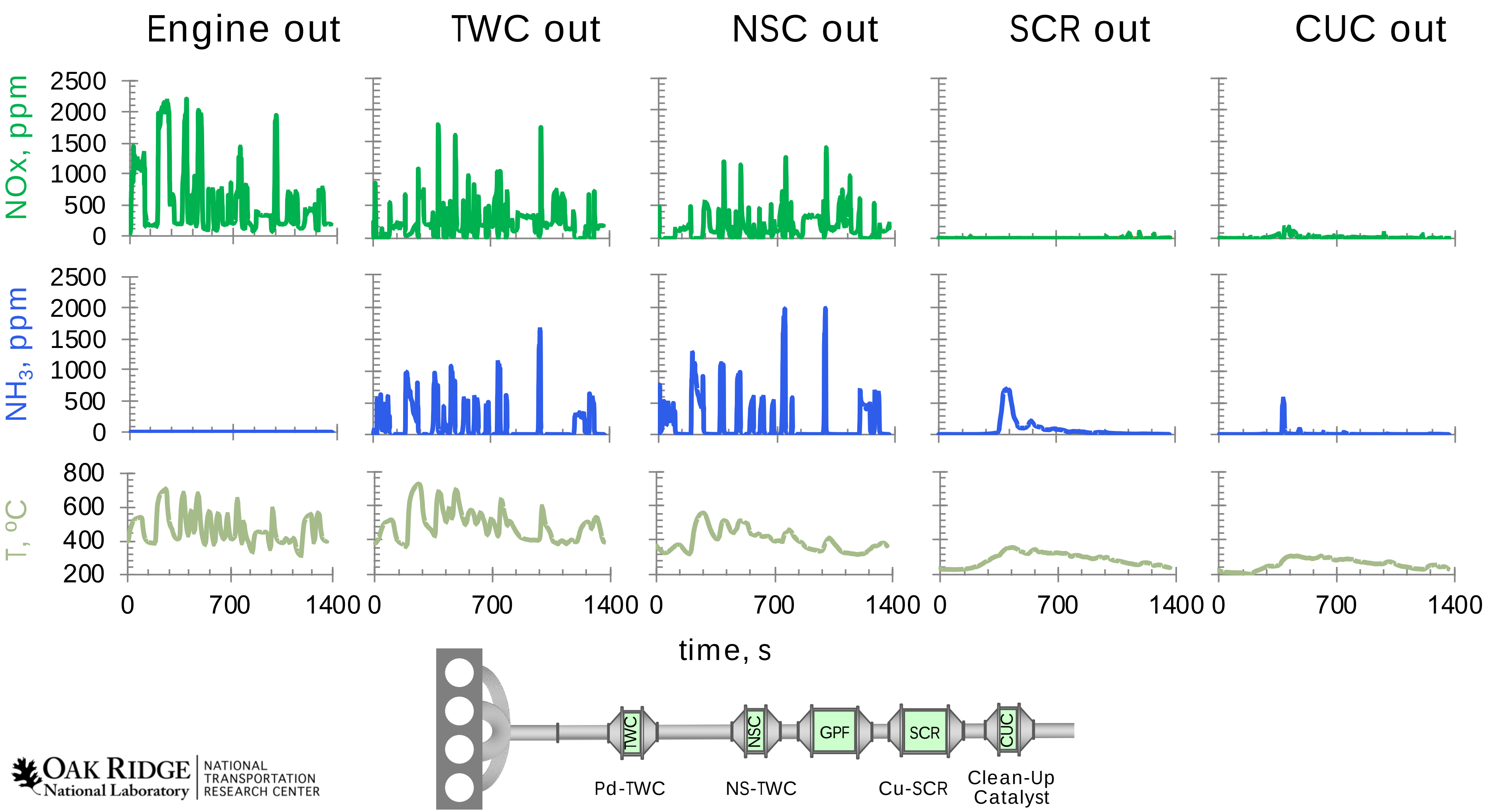
Fuel contained 8 ppm of sulfur

8.3 g/liter-engine total PGM

Some catalyst functions can be combined into one brick

Investigate operating strategies for maximum fuel efficiency while meeting Tier 3 emission standards

- NOx is essentially eliminated at SCR
- NH_3 slip still observed, with some NH_3 converted back to NOx over CUC catalyst



5-function emission control system enables efficient NH_3 generation and utilization for lean NOx control

NOx and NH_3 inventory

Engine out

Rich NOx is ~3x lean NOx, potential for ~3x NH_3

TWC out

Some rich NOx is converted to NH_3 by TWC

NSC out

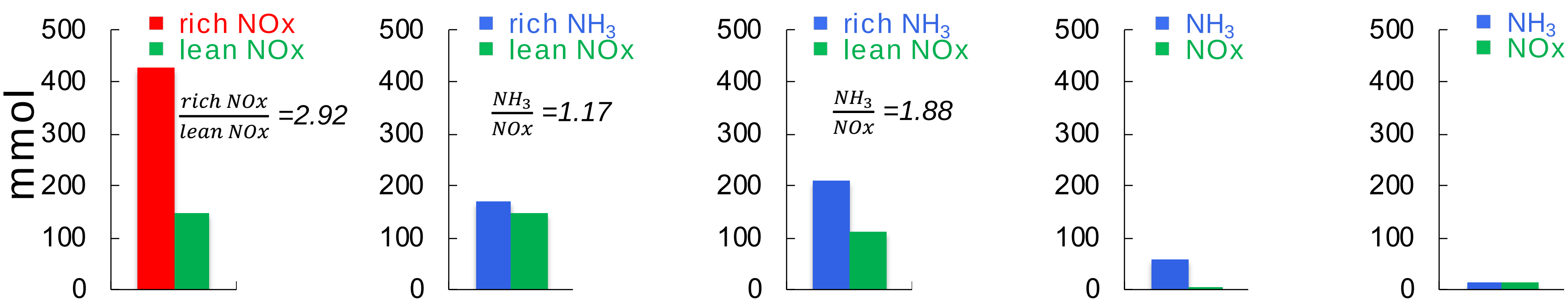
Some lean NOx is stored, additional NH_3 made from stored NOx by NSC

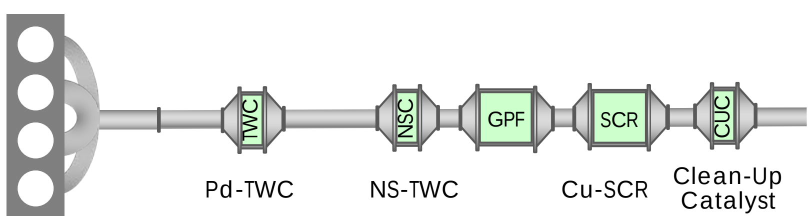
SCR out

NOx eliminated, NH_3 slip observed

CUC out

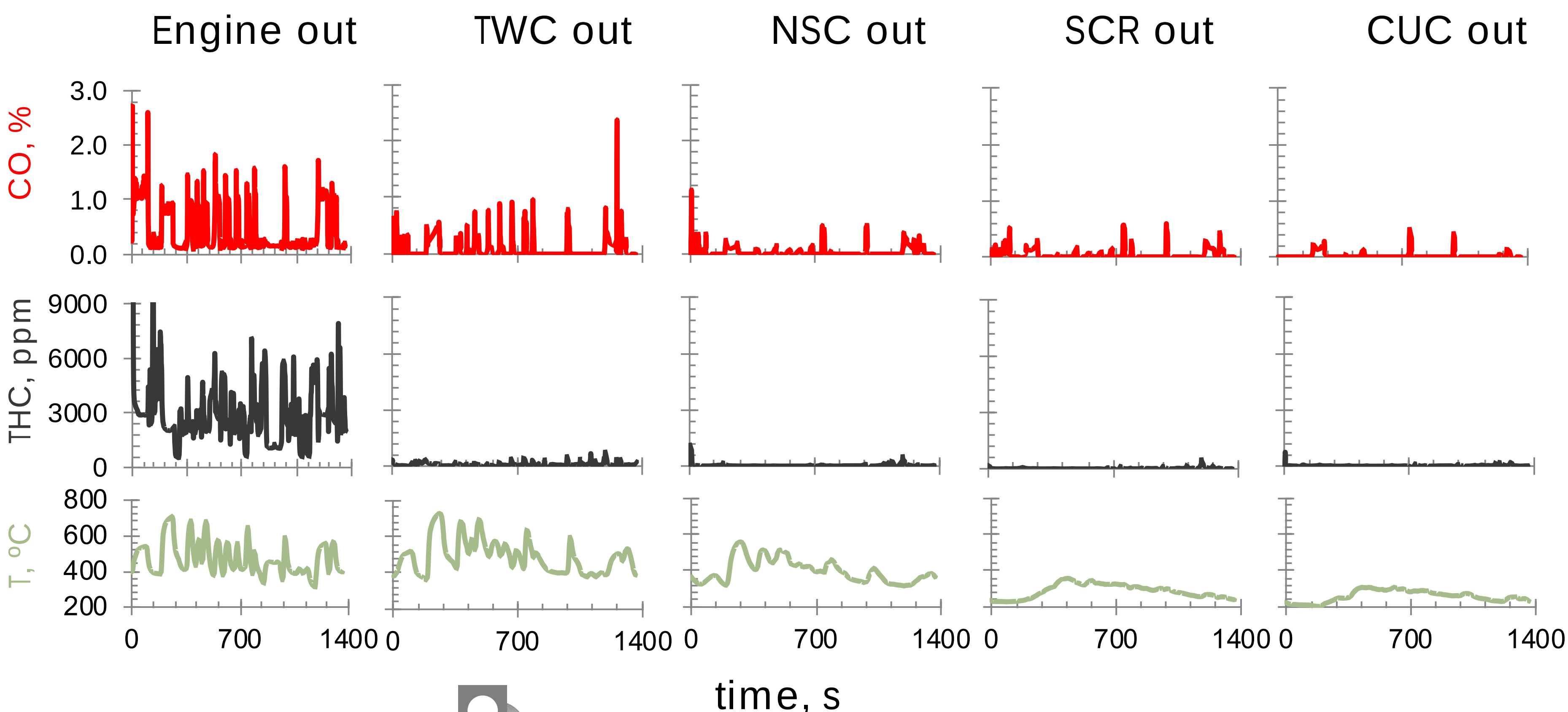
NH_3 slip reduced, with some NH_3 converted to NOx

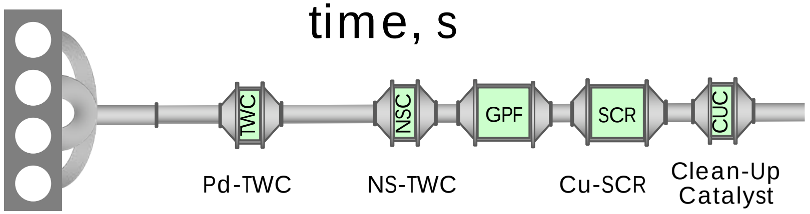




Investigate operating strategies for maximum fuel efficiency while meeting Tier 3 emission standards

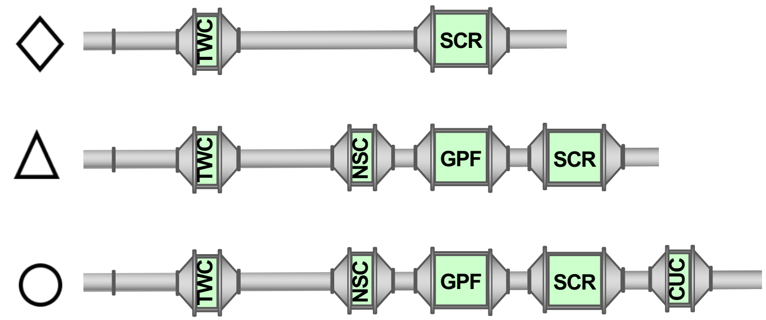
- High CO slip during rich operation
- THC slip is low during both lean and rich operation, slightly increases during prolonged lean operation

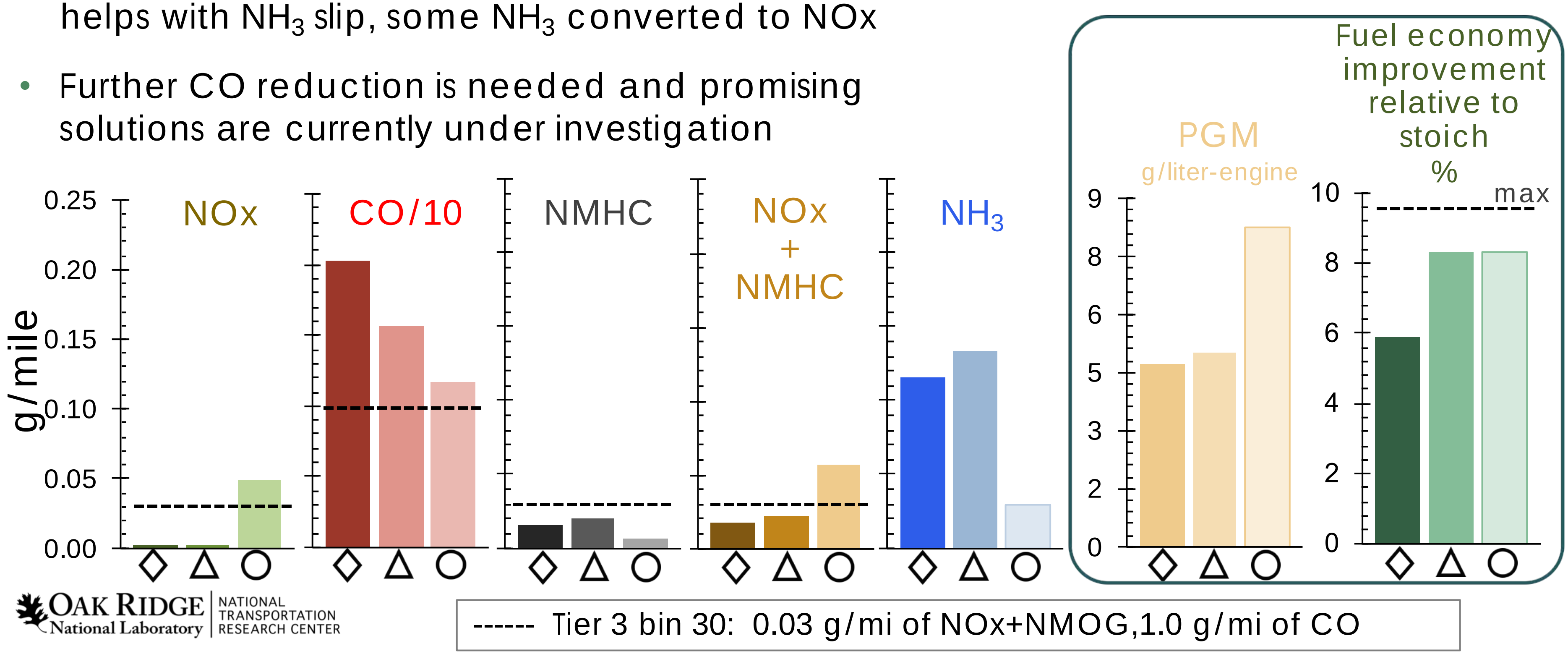




Up to 8.3% fuel efficiency improvement achieved with improved system architecture

- TWC+NSC combination enables more efficient NH_3 generation and provides pathway for increasing fuel economy benefit
- 0.03 g/mile NOx+NMOG tailpipe emissions demonstrated with FUL equivalent performance
- CUC decreases CO and HC emissions and helps with NH_3 slip, some NH_3 converted to NOx
- Further CO reduction is needed and promising solutions are currently under investigation





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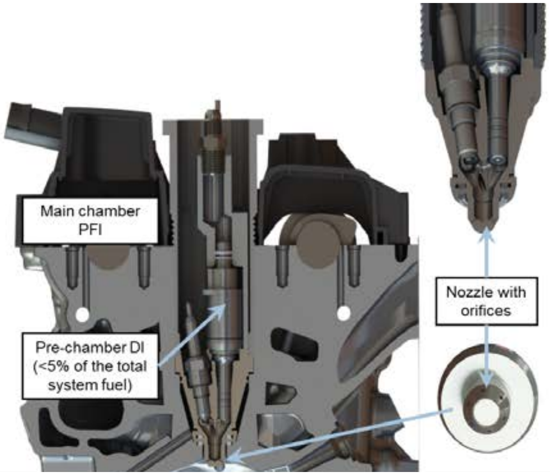
ORNL procured MAHLE TJI engine for lean gasoline emission control research

MAHLE TJI will be used to generate a wide range of exhaust conditions that will allow us to fully investigate the emission control system functionality

- BMW lean gasoline engine is 10+ years old
  - concerns about longevity and availability of replacement parts
- MAHLE TJI engine procured as a new lean gasoline engine platform
  - based on a 2.3L Ford EcoBoost engine platform
  - provides relevant turbo-boosted stoichiometric baseline for comparison
  - offers wider range of ultra lean operation
  - capable of better control over exhaust composition and temperatures

MAHLE Turbulent Jet Ignition



Images from MAHLE

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Remaining Challenges	Future Work*
• CO and HC control during rich conditions	• Experiments planned on flow reactor and engine platform to evaluate impact of clean-up catalysts • Potential addition of secondary air
• Maximize fuel efficiency while maintaining or further reducing emissions	• Install MAHLE TJI engine to expand lean operation map for higher fuel efficiency and lower engine out emissions • Flow reactor and engine evaluations of additional catalyst technologies and architectures • Optimizing NH_3 generation control using real-time feedback from RF-based NH_3 storage sensor
• SCR performance at full useful life	• Engine evaluation of new SCRs provided by Umicore and aged at SGS to full useful life

** - subject to change based on funding levels*

Responses to 2018 reviewer comments

Summary of Reviewers' Feedback:	Project Responses:
Investigate SCR aging under passive SCR conditions	• Experiments are planed on engine and bench flow reactor to address this issue
Improve CO cleanup	• Demonstrated CO and HC reduction with a clean-up catalyst • Additional clean-up catalysts formulations provided by Umicore are under investigation • Addition of air injection is under consideration
Pathway for higher fuel efficiency	• Demonstrated pathway to improve from 5.9% to 8.3% • Procured new lean gasoline engine platform • Flow reactor and engine evaluations of additional catalyst technologies and architectures

Summary

- Relevance
  - Lean GDI engine emission control enables potential 10-15% fuel efficiency gain for gasoline-dominant U.S. light-duty fleet
- Approach
  - Bench flow reactor, engine, and aging studies are combined to study fuel efficiency and emissions relative to Tier 3 standard
- Technical Accomplishments
  - Using 5-function emission control system achieved 8.3% fuel economy benefit compared to 5.9% fuel efficiency improvement demonstrated last year, while meeting Tier 3 NOx+HC (0.03 g/mi)
  - Procured Mahle TJI engine for lean gasoline emissions research
  - Completed analysis of sulfur effects on isolated reactions on two TWCs
- Collaborations
  - GM, Umicore, and the University of South Carolina are primary partners
- Future Work *(subject to change based on funding levels)*
  - Flow reactor and engine platform to evaluate impact of clean-up catalysts
  - Install Mahle TJI and a new transient dynamometer at ORNL
  - Evaluate additional catalyst technologies and architectures
  - Optimize NH_3 generation using real-time feedback from RF-based NH_3 sensor
  - Evaluate effects of aging on SCR catalyst under passive SCR conditions

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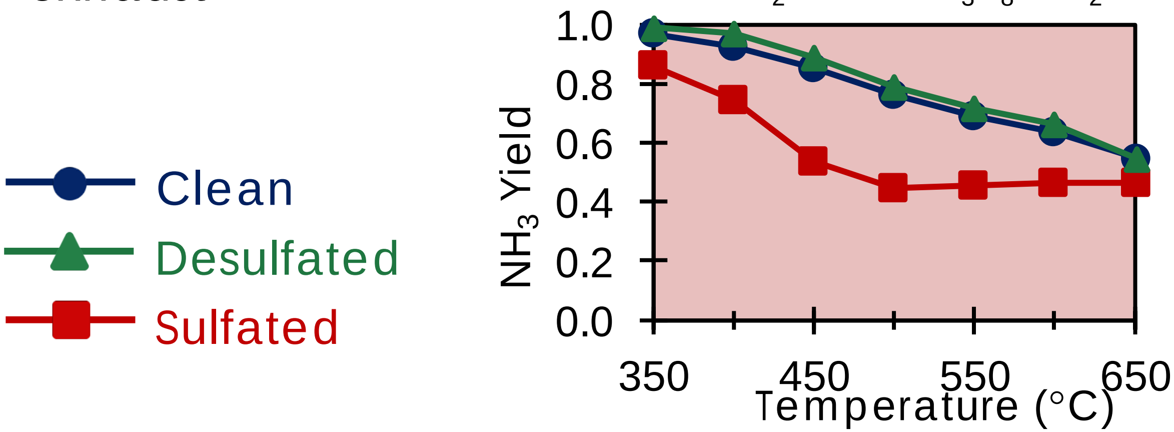
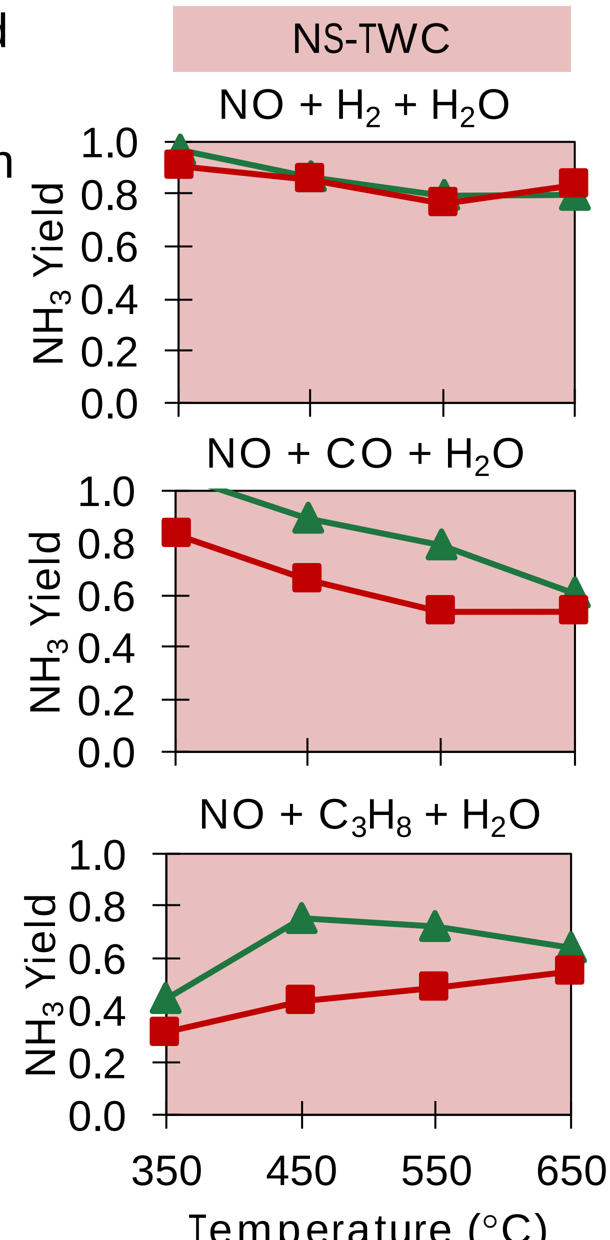
Technical back-up slides

Impact of sulfur on NH_3 selectivity

- Effects of SO_2 on hydrothermally aged Pd-TWC and NS-TWC investigated on bench flow reactor
  - Both catalysts show decrease in NH_3 production from sulfation
- Catalysts able to maintain NH_3 production from H_2 after sulfur exposure
- NH_3 production from CO and C_3H_8 decreased, indicating CO and HC pathways to NH_3 production impacted in full simulated exhaust

NS-TWC Simulated Exhaust: NO + H_2 + CO + C_3H_8 + O_2

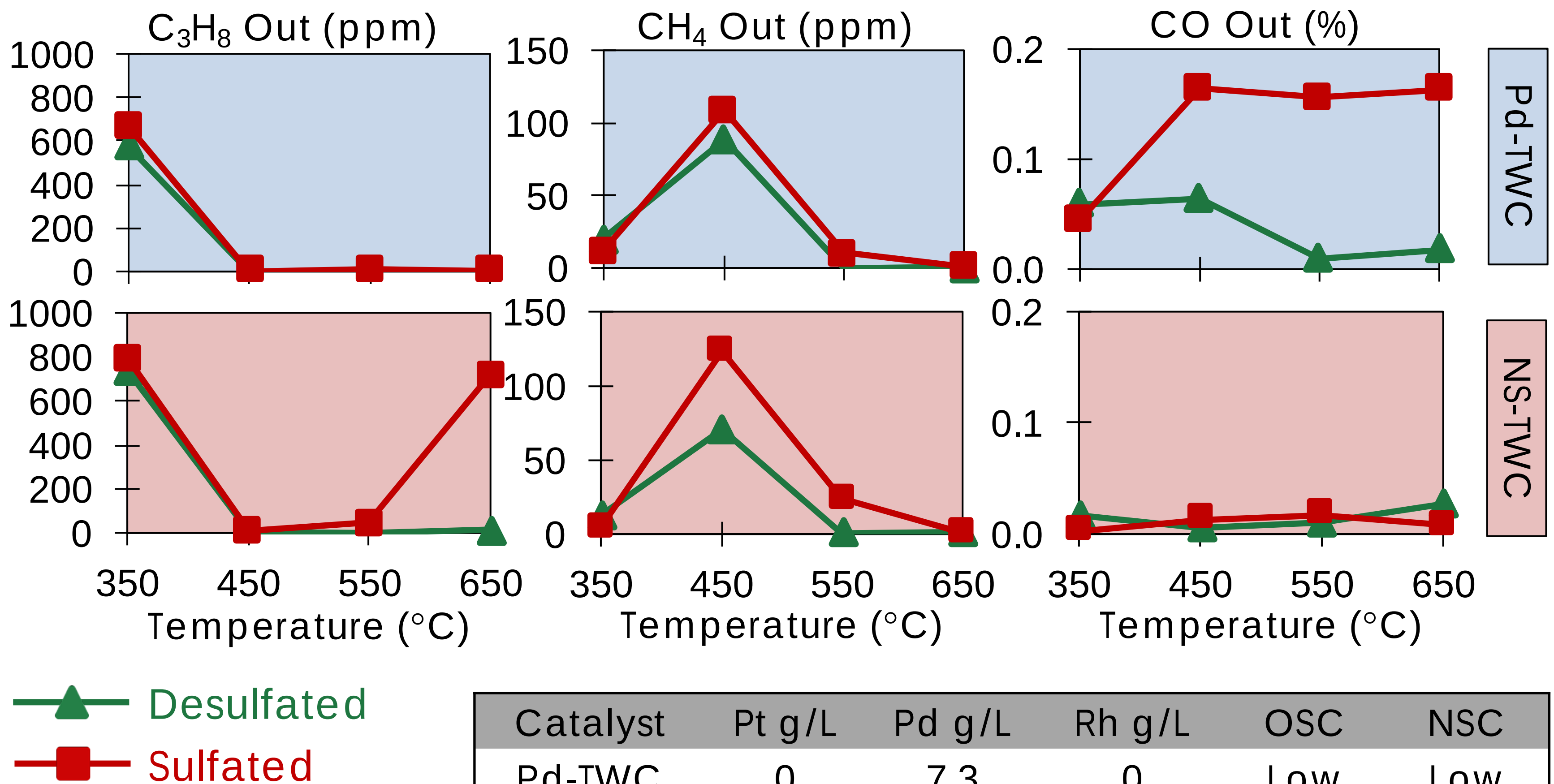




Catalyst*	Pt g/L	Pd g/L	Rh g/L	OSC	NSC
Pd-TWC	0	7.3	0	Low	Low
NS-TWC	2.47	4.17	0.05	High	High

Sulfur impacts on WGS and steam reforming varies with PGM

- Relative deactivation depends on catalyst formulation:
  - Water gas shift strongly deactivated on Pd-TWC
  - Steam reforming strongly deactivated on NS-TWC



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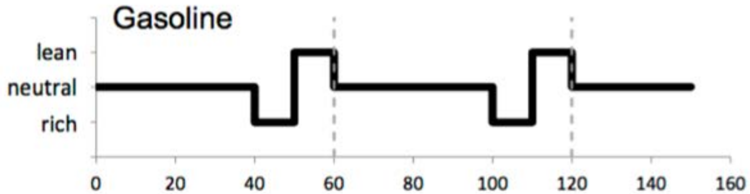
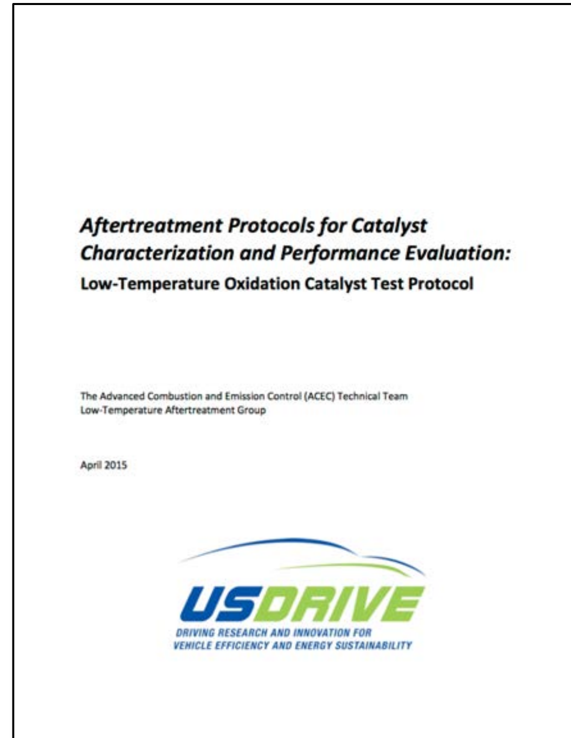
Pd-TWC	0	7.3	0	Low	Low
NS-TWC	2.47	4.17	0.05	High	High

TWCs thermally aged at SGS using LTAT aging protocol, Umicore Cu SCR previously aged on engine



- Aging Cycle
  - Stoich: 40 seconds, lambda=1
  - Rich: 10 seconds, lambda=0.91
  - Lean: 10 seconds, lambda=1.33
- Aging inlet temperature
  - 800C for closed coupled
    - Malibu and ORNL-1
  - 700C for underfloor
    - ORNL-3 and ORNL-5
- Aging time
  - 50 hours
- Catalyst space velocity
  - 30K hr^{-1}



Aftertreatment Protocols for Catalyst Characterization and Performance Evaluation:

Low-Temperature Oxidation Catalyst Test Protocol

The Advanced Combustion and Emission Control (ACEC) Technical Team
Low-Temperature Aftertreatment Group

April 2015

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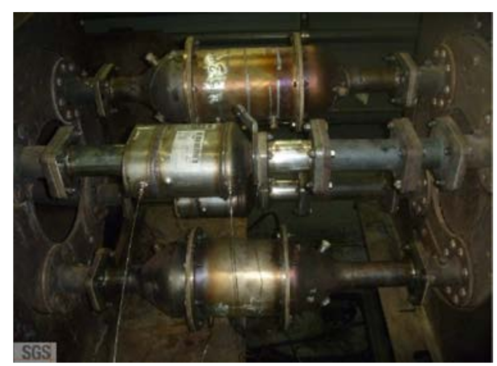
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

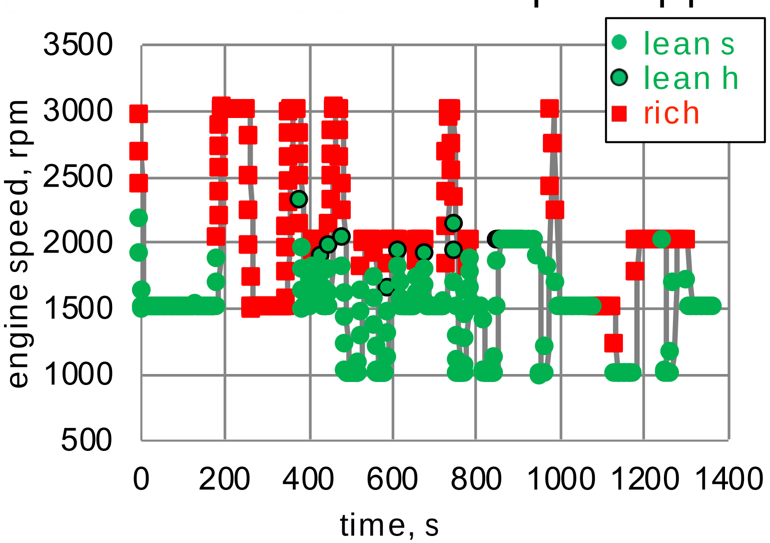
https://cleers.org/wp-content/uploads/2015_LTAT-Oxidation-Catalyst-Characterization-Protocol.pdf



Investigate exhaust architectures and operating strategies for better fuel efficiency

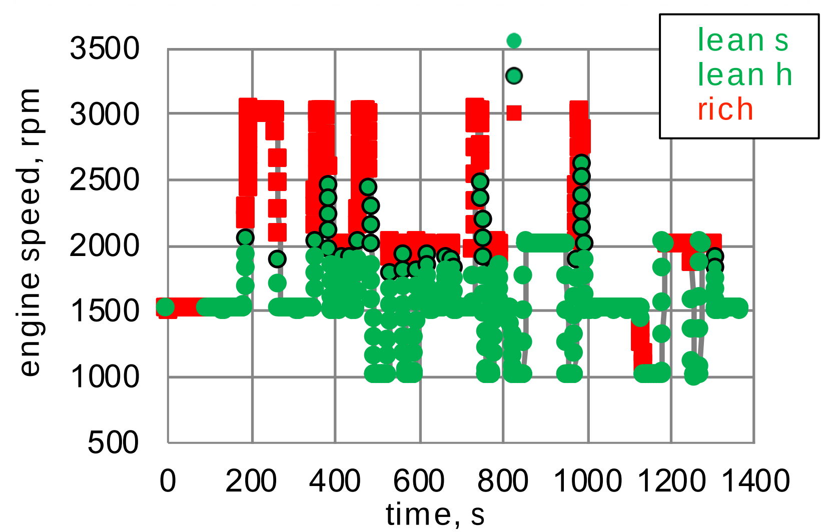
TWC + SCR

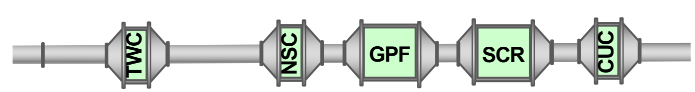
- Partially preload SCR with NH_3 to have enough for first 200s
- Exclude lean homogeneous
- Operate at λ=0.97 under most condition, when SCR temperature too high, operate λ=0.99
- Switch to rich if NOx slip >10 ppm



TWC+NSC+GPF+SCR+CUC

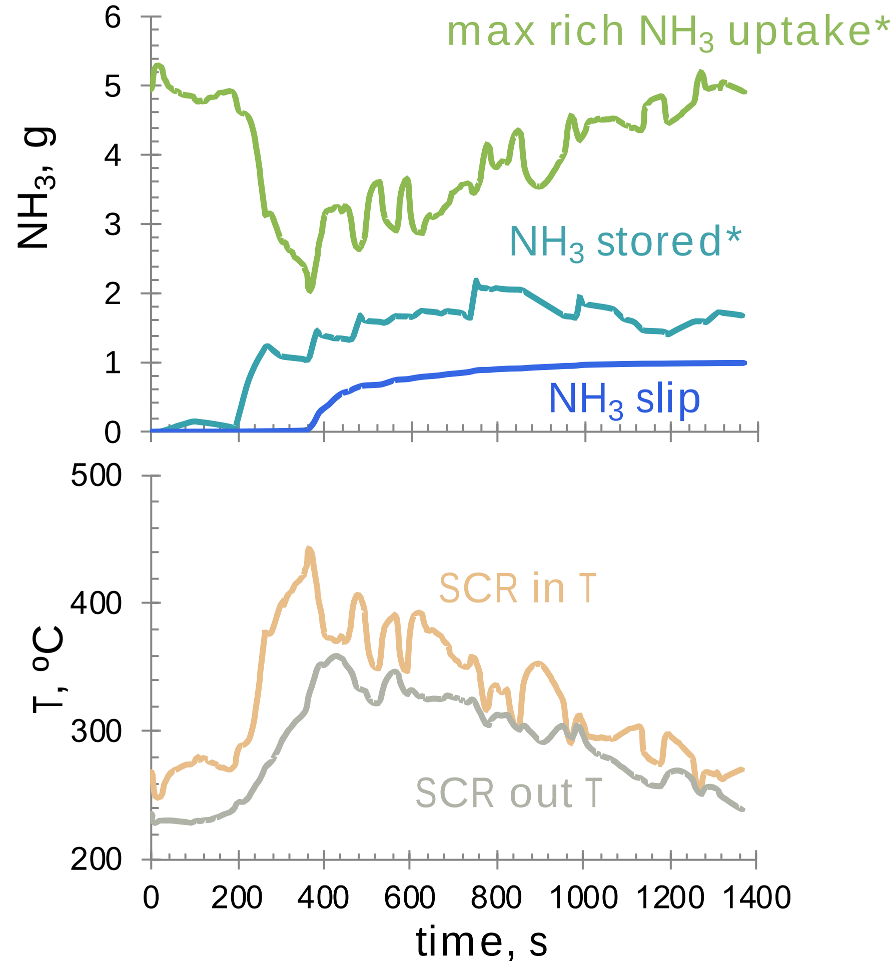
- Operate rich λ=0.99 first 100s (cold start)
- Include some lean homogeneous
- Operate at λ=0.98 under most condition, when SCR temperature too high, operate λ=0.99
- Switch to rich if NOx slip >20 ppm

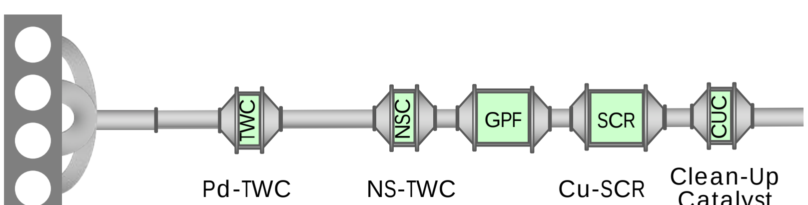




While acceleration transients offer natural opportunities for fuel efficient NH_3 generation, NOx reduction can be limited due to low NH_3 storage at high temperatures

- Acceleration events
  - increase NH_3 generation potential b/c of high engine-out NOx
  - create opportunity for fuel efficient NH_3 generation b/c engine runs stoich or slightly rich already
- But long accelerations increase SCR temperature limiting NH_3 storage
- Effective NH_3 utilization needed to minimize NH_3 slip and improve fuel efficiency
  - increased high temperature SCR storage capacity
  - Improved control strategy





*NH_3 stored = NH_3 in- NOx in

*calculated based on rich NH_3 uptake experiments